Development of a elasto-viscoplastic model to simulate the solid-fluid transition: application to mudflows on the Vaches Noires cliffs, Normandy, France

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SUMMARY: An elasto-viscoplastic model has been developed to simulate the solid-fluid transition by coupling two constitutive regimes: Modified Cam-Clay model (MCC) for the elasto-plastic behavior and Hershel-Bulkley rheological model (HB) for the viscous behavior. The second-order work criterion has been used to describe the solid-fluid transition. The model was applied to mudflows affecting the Vaches Noires cliffs (Normandy, France).

Keywords: elasto-viscoplastic modeling, mudflows, solid-fluid transition

Introduction

Numerical modelling of landslides evolving into mudflows (Cruden and Varnes 1996) requires to take into account the solid-fluid transition of geomaterials (Coussot and Ancey 1999; Prime 2012; Prime and Dufour 2013; Li *et al.* 2016) as these phenomena combine an initiation phase, transport and propagation, and a cessation phase (Fort *et al.* 2015). Each phase corresponds to a material state that can evolve from solid to fluid, and finally turns back to solid. For the movement initiation phase, the behavior of these materials is described by elasto-plastic behavior laws within the framework of soil mechanics (Magnan and Mestat 1997; Darve and Sibille 2016). However, these geomaterials may liquefy, leading to a viscoplastic flow. In such conditions, they are described by fluid rheology (a branch of mechanics concerned with non-elastic solids and complex non-Newtonian fluids) via viscoplastic behavior laws (Balmforth and Craster 2001; Prime and Dufour 2013; Li *et al.*2016; Han *et al*. 2019). These phase transformations are complex because they are non-linear over time. A slow-creep landslide may suddenly accelerate under the effect of precipitation, or remain unchanged after the same rainfall event.

Numerical modeling of these geomaterials requires a constitutive law that adapts to variations in material characteristics. It should be able to accurately describe the material in the different states, solid and fluid, as well as the transition between these two states. There are few models that consider both the elasto-plastic behavior of solid soils (quasistatic regime) and the viscous behavior of fluidized soils (flow regime), as well as the transition between the two regimes. A notable achievement was obtained with the work of Prime in 2012, who proposes a model combining these two behaviors, enriched with a transition criterion based on the second-order work computation (Hill 1958; Prime 2012; Prime and Dufour 2013).

During the initiation phase, the behavior of these materials is described by an elasto-plastic relation within the framework of soil mechanics. When these materials fluidize and give way to mudflows, their behavior is determined by fluid rheology, through viscoplastic constitutive

relations. These state transitions are intrinsically complex, as they evolve non-linearly over time.
Our aim was to develop an operational tool to model numerically the solid-fluid transition using the commercially available software package, *FLAC* 8.1. This tool integrates two constitutive models: Modified Cam-Clay (MCC) model for the elasto-plastic behavior and Hershel-Bulkley (HB) rheological model for the viscous behavior. The solid-fluid transition is detected by using the second-order work criterion. It should be noted that this numerical development is not designed to simulate propagation in the strict sense.

Modeling strategy
The FLAC 8.1 software, based on the finite-difference method, was selected. This method explicitly solves local problems step by step. It is popular for its ability to handle large-scale problems and for optimizing calculation time. In addition, FLAC software makes parametric studies easy thanks to its FISH scripting language. It also offers a wide range of elastoplastic behavior laws (e.g., Modified Cam Clay), and enables calculations with advanced hydromechanical coupling, adaptable to the user's needs (Cundall et al. 1993).
Since the behavior laws must manage instantaneous elasto-plastic deformations as well as viscous deformations, with a transition criterion between these two behaviors, the following numerical strategy was adopted (Fig. 1):

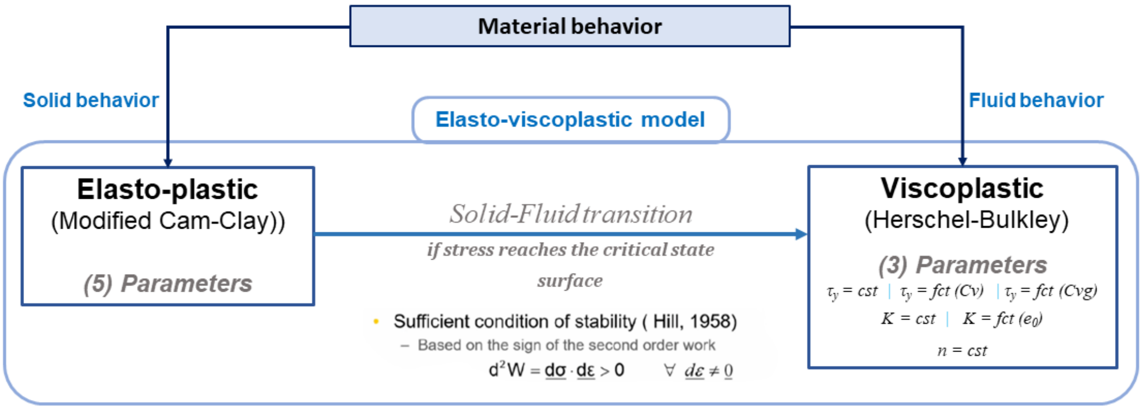

Figure 1. Diagram of the new constitutive model of elasto-viscoplastic behavior.

Elasto-plastic behavior law: Modified Cam-Clay model (MCC), with work-hardening adapted to the modeling of remolded clay materials (Mestat and Riou 2002);
Viscous behavior law: Hershel-Bulkley (HB) rheological model, which is the most widely used model for describing mudflows. It also offers the possibility of using evolving parameters, to cover the change in rheological parameters as a function of volume concentration and grain size distribution (Pellegrino and Schippa 2018);
Solid-fluid transition criterion: it was desirable to use the second-order work criterion as the phase transition criterion (Hill 1958). However, since the Cam-Clay model is an associated model, the second-order work criterion (W_2) coincides with the boundary plasticity criterion.

The constitutive model was implemented as an user-defined model in the *FLAC* software. Consolidated-drained triaxial tests were carried out on samples to calibrate the constitutive parameters.

Results

In order to simulate the landslide event, it is necessary to determine as accurately as possible the period of the event, and establish the relevant hydrogeological conditions. This requires information on the water table variation on the slope and within the flow, as well as on precipitation variation. In addition, the event was characterized by assessing displacements and initial flow velocities. The geometric model of the selected flow together with the hydraulic conditions are illustrated in Figure 2.A.

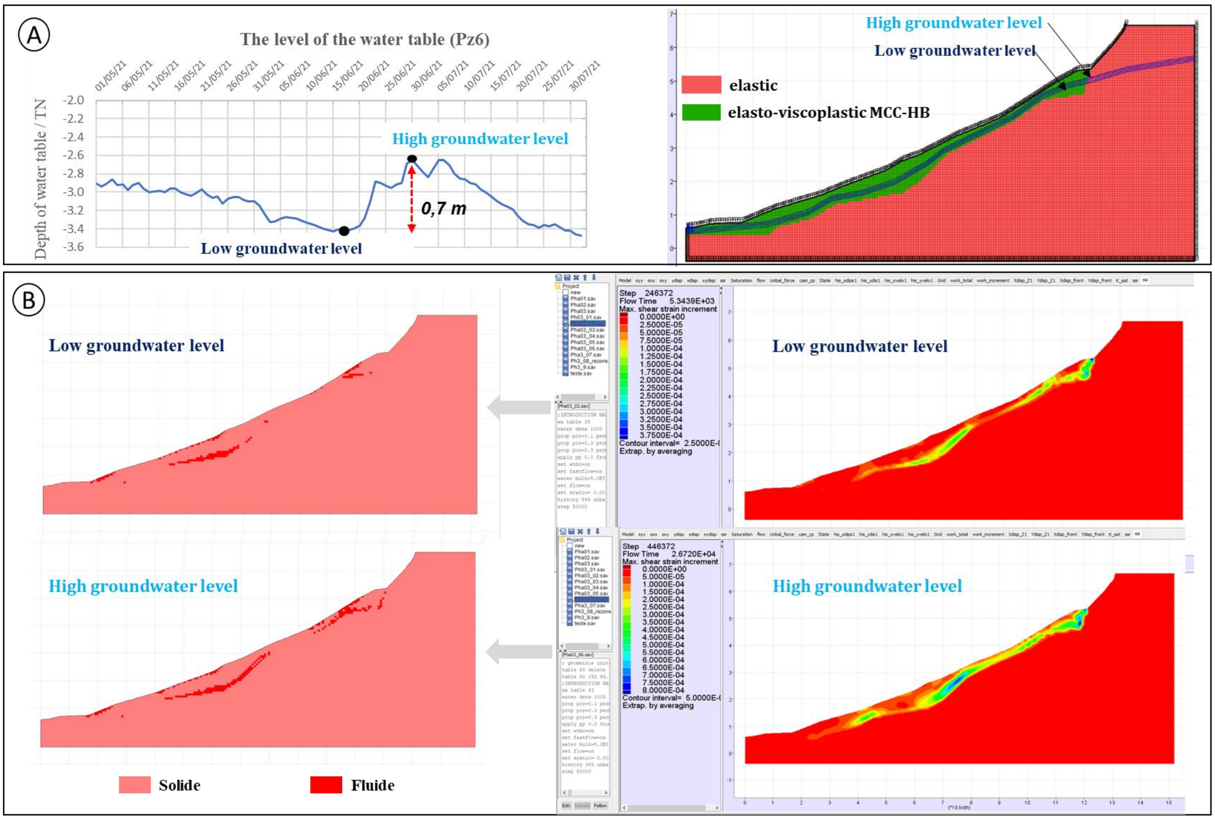

Figure 2. Application of solid-fluid transition modelling; A (left) Variation in water table level in the slope, represented by Pz6; A (right) Geometric model and introduction of hydraulic conditions; B (left) Solid-fluid transition in the flow with increasing water table level; B (right) Evolution of maximum shear strain in the flow with changing water table.

The initial stress state within the slope should be reproduced. Then, the hydraulic conditions were specified. Hydromechanical calculations were then performed, considering the evolution of the water table. The creep calculation was activated using the HB model.

Figure 2.B shows the transition between the solid and fluid regimes, under the control of the variations in hydraulic conditions. As the water table evolves, certain zones of the flow undergo a phase transition from solid to liquid. They transition from an elastoplastic regime, where the constitutive behavior is described with the MCC model, to a time-dependent viscous regime, where the constitutive behavior is described with the HB model. These transitions become increasingly pronounced with the evolution the groundwater inside the mudflow.

Discussion - conclusion

Numerical modeling of the solid-fluid transition using this new approach has overcome the limitations of viscous models, which present challenges in correctly representing solid behavior (Prime et al. 2014). This approach adequately describes the solid behavior with instantaneous elastoplastic deformations, as well as the fluid behavior with time-dependent viscous deformations. This implementation has been successfully carried out on in the *FLAC* software (based on a Lagrangian approach), which is widely recognized within the geomechanics community. The aim is to ensure that these developments can be used in geotechnical engineering situations, providing an advanced modeling to better understand the behavior of geomaterials after the failure phase. However, in the context of this initiative, our model is incapable of detecting solid-fluid transitions that may occur before reaching the failure criterion, highlighting the need for a non-associated elastoplastic model with W_2 as the transition criterion. Moreover, the model is limited to only considering the initial phase of the solid-fluid transition, without the ability to handle the reverse transition fluid-solid. This limitation restricts our ability to track displacements and model the evolution of the mudflows. It should also be noted that this numerical tool is not designed to simulate the propagation *stricto sensu*, as this requires additional numerical methods based on hybrid approaches (Eulerian / Lagrangian) such as MPM (Material Point Method), FEMLIP (Finite Element Method with Lagrangian Integration Points), etc. (Sulsky and Schreyer 1996; Dufour 2005; Prime and Dufour 2013; Vicari *et al.* 2022).

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